Available online at www.sciencedirect.com
SCIENCE DIRECT

Renewable and Sustainable Energy Reviews
8 (2004) 73–90

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

# Approaching the Kyoto targets: a case study for Basilicata region (Italy)

M. Salvia [a,*], F. Pietrapertosa [a,c], C. Cosmi [a,d], V. Cuomo [a], M. Macchiato [b,d]

[a] *Istituto di Metodologie per l'Analisi Ambientale, Consiglio Nazionale delle Ricerche, C.da S.Loja, I-85050 Tito Scalo (PZ), Italy*
[b] *Dipartimento di Scienze Fisiche, Università Federico II, Via Cintia, I-80126 Napoli, Italy*
[c] *Dipartimento di Ingegneria e Fisica dell'Ambiente, Università degli Studi della Basilicata, C.da Macchia Romana, I-85100 Potenza, Italy*
[d] *Istituto Nazionale di Fisica della Materia, Unità di Napoli, I–80126 Napoli, Italy*

Received 9 April 2003; accepted 9 May 2003

**Abstract**

Approaching the national Kyoto Protocol (KP) targets involves a re-definition of the actual configuration of local energy systems. This study deals with a local scale application of the IEA-MARKAL models generator, in which the anthropogenic system of Basilicata Region (Southern Italy) is investigated to support the definition of coherent long-term strategies and sound climate protection policies. A scenario by scenario analysis points out the behaviour of the optimal mix of fuels and technologies in the presence of carbon dioxide emissions constraints. Trade off curves and reduced costs analyses outline the most effective actions for contributing to the national KP targets, with particular emphasis on the interventions in Civil (Residential, Commercial & Services) and waste management sectors.


*Keywords:* Local energy planning; MARKAL models generator; Greenhouse gases emissions

**Contents**



* Corresponding author. Tel.: +39-971-427-207; fax: +39-971-427-271.
*E-mail address:* salvia@imaa.cnr.it (M. Salvia).

1364-0321/$ - see front matter 
doi:10.1016/j.rser.2003.05.001

## 1. Introduction

The Kyoto Protocol (KP), negotiated by over 160 countries in December 1997, follows the 1992 UN Framework Convention on Climate Change (UNFCCC) and contains legally binding greenhouse gas (GHG) emission targets for developing countries in order to prevent anthropogenic interference with the climate system. Italy, as part of the so-called Annex B parties, has to reduce its overall GHG emission level by at least 6.5% below 1990 levels (as concerns $CO_2$, $CH_4$, $N_2O$) or 1995 levels (as concerns HFCs, PFCs, SF6) in the commitment period 2008–2012.

Recognising the key-role of technology innovation in the reduction of GHGs on a medium-long term [1], the Italian Law no. 120 of 1 June 2002 ratifies the KP and identifies a set of guidelines on policies and measures, mainly focused on an increase of the energy efficiency of the national economic system and a more consistent use of renewable energy sources (promotion of biomass-based combined heat and power plants, promotion of solar thermal, wind, photovoltaic, waste and biogas-based power plants) [2]. These provisions are applied on a national system characterised by an increasing trend (+5.4% between 1990 and 2000) of the carbon dioxide ($CO_2$) emissions, which account for 84.7% of all greenhouse gas emissions in $CO_2$-equivalent [3].

The elaboration of a national climate change strategy requires the implementation of many measures in different economic and technological sectors, as outlined previously by the Italian Guidelines for national policies and measures of greenhouse gases emissions [4]. These measures cannot leave out of consideration the new role of the regions and local government bodies, which on 5 June 2001, signed an Agreement Protocol aimed at reducing emissions of greenhouse gases into the atmosphere [5].

Focused on the case study of Basilicata, a South-Italian region, this research is aimed to provide energy analysts and local energy planners with an assessment of strategies, measures and interventions on local energy systems, aimed at coping with the national KP targets.

Based on the MARKAL models generator of the International Energy Agency, MARKAL-Basilicata was implemented to perform a comprehensive analysis of the

regional energy system, evaluating the feasibility of reductions in fossil fuels consumption, improvements of technological efficiency, and the promotion of renewable energy sources. The effects of carbon dioxide constraints on the model solutions are also discussed with reference to changes in technological choice, repercussions on the system costs and effects on local air pollutants.

## 2. Methodology

Much progress has been made up till now in the development of modelling tools to support the decision making process in different sectors (Agriculture, Energy, Environment, Transports).

As concerns the energy sector, a recent methodology developed under the IEA programme for Energy Conservation in Buildings and Community Systems, Annex 33, is the Advanced Local Energy Planning (ALEP). ALEP is aimed to develop consistent "comprehensive" energy plans, by a combination of long-term strategy planning with a more detailed one (related to subsystems). It is based on the integration of different tools (databases, comprehensive models, auxiliary tools) and its results serve as the basis for "a group-dynamic approach to achieve consensual solutions among the different actors who are involved in the implementation of this plan" [6,7].

The focal tool of the ALEP methodology is represented by the MARKAL models generator [8–10], a widely applied bottom-up, dynamic, originally and mostly a linear programming (LP) model developed by the Energy Technology System Analysis Programme (ETSAP) of the International Energy Agency [11]. MARKAL provides a comprehensive approach of energy and commodities system: it is driven by end-use commodities demands and is characterised by an integrated representation of extraction, production, trading, transformation and end-uses of energy forms and some materials. The optimisation routine allows users to identify the least-cost combination of technologies and fuels for each time period considered (usually 3-year or 5-year). A variety of different constraints may be applied to provide a consistent representation of the energy system (e.g. for balancing energy inputs and outputs) and to analyse the effects of environmental and policy issues (for instance introducing sectoral or system-wide emissions limits on an annual basis or cumulatively over time) on the time horizon, in compliance with the exogenous constraints.

These features make MARKAL a powerful tool for providing policy makers and planners in the public and private sector with an understanding of the interplay between the macro-economy and energy use [12]. The growing amount of MARKAL experience world-wide has given rise to various model variants, whose main characteristics can be found in the literature [13–19].

Whatever is the variant chosen, MARKAL users can generate suited models, different for time horizon, spatial scale and technology detail, according to the study objectives. In particular it allows users to enlarge the typical boundaries of system engineering models, often focused on single sectors (e.g. energy, transportation, waste management) and on single phases of the life cycle of a process/pro-

duct. This enlargement towards a “comprehensive” approach makes it possible to take into account the entire chain of energy and material flows, evaluating the environmental costs due to each phase (from primary production to disposal). This is particularly useful in the definition of strategies for reducing GHGs emissions, where material flows and, in particular, waste produced by the anthropogenic activities system play a crucial role [20].

In this study a MARKAL-generated subsystem model (WAMMM—WAste Management MARKAL Model) was used for the analysis of the waste management system of the Basilicata region. This choice assured that both the subsystem and the comprehensive models have the same structure and, in particular, the same multi-period desegregation.

Results obtained at this stage, described in previous papers [21,22], showed that the energy system model MARKAL can be usefully used on a local scale to define sustainable integrated waste management strategies. Therefore, these results were included in the comprehensive model, MARKAL-Basilicata, implemented to investigate on the possible contribution of local communities to national GHGs emissions reduction strategies, focusing on the contribution of different macroeconomic sectors and the waste management system.

MARKAL-Basilicata is characterised by a multi-region approach, obtained by using the Regional MARKAL (R-MARKAL) variant. This variant allows modellers to simultaneously optimise energy systems related to two or more “regions”, administrative areas with their own productive and end-uses systems, linked by energy and material flows (electric energy, process heat, waste, etc.). Although R-MARKAL has been mostly applied up till now on a supranational scale to analyse emission trading mechanisms between national energy systems [13], R-MARKAL can also be used to support energy-environmental planning at the local scale [23], providing sector specific information.

## 3. The REMS of MARKAL-Basilicata

The MARKAL database is organised and structured around the concept of Reference Energy and Material System (REMS), which is a network description of energy and material flows in the concerned region, with a precise description of all technologies that are involved (or potentially involved) in the production, transformation and use of various energy forms.

The useful demands, which drive the model, correspond to energy services required by the economic activities of the local system and are satisfied by demand devices (categorised by sector) that transform energy carriers into useful demands. The energy carriers are produced by processes (when they correspond to storable energy forms, like fossil fuels), or by conversion technologies (when they correspond to electricity or low temperature heat) [24].

Each technology is described by a set of parameters, which includes technical (efficiency, capacity factor, physical lifetime), economic (investment costs, fixed/variable operating and maintenance costs) and environmental data (emissions factors). Therefore, the specification of new technologies, which are less energy or car-

bon intensive, allows the user to explore the effects of these choices on total system costs, changes in fuel and technology mix, and the levels of greenhouse gases and other emissions [12].

The REMS of MARKAL-Basilicata was built-up on the basis of the main characteristics of the local end-use energy services (demands), using a different level of desegregation in relation to data availability, possible use of renewable sources and application of environmental restrictions. The end-uses demands are met by a network of technologies which, initially, reproduces the actual configuration and, subsequently, take into account technological development (turnover of devices, introduction of renewable energy sources, changes in waste management options, etc.).

The analysed sectors are: Agriculture, Civil (Residential, Commercial and Services), Industry (Food and Drink, Paper, Chemical, Mining, Building materials, Mechanic, Iron and steel industry, Textile, Glass-Ceramics, Buildings, Other industries, electric energy, gas and water), Transport (Railway and Road) and Waste management (plastic films from Agriculture, municipal solid waste—MSW—and secondary raw materials, industrial waste streams).

An aggregated representation of the MARKAL-Basilicata REMS is represented in Fig. 1. It shows that two dummy "regions" were identified in order to perform a joint optimisation of the regional anthropogenic system. The first region models the "supply side" (waste management and conversion technologies), whereas the second one regards the "demand side" (Agriculture, Residential, Commercial and Services, Industry and Transport). The two regions, modelled as different energy systems, are linked by energy and material flows. In particular the conversion technologies and the incinerators (Region 1) supply electricity to all the sectors of Region 2 and low-temperature heat to residential areas (Civil sector). At the same time the waste produced by the anthropogenic activities system becomes an input flows for the regional waste management system. In such a way a comprehensive analysis of both the commodities production phase and their disposal phase is performed, pointing out the optimal solution for each sector and the role of energy and material flows in the achievement of sustainable strategies.

As concerns the Waste management sector, in compliance with the national laws [25], the landfilling of waste streams (which represent the actual situation) is progressively substituted by an integrated system of technologies aimed at waste valorisation and pollution prevention. Taking into account the main results obtained by the applications of the WAMMM model, the waste handling system for municipal solid waste (MSW) is based on the following actions: separate collection of secondary raw materials (SRM: paper/cardboard, plastics, glass, aluminium cans, etc.), mechanical pre-treatments (by rotary drum screening), combined use of three main processes: incineration with energy recovery of the "dry" fraction resulting from screening, aerobic stabilisation of the "moist" fraction and high-quality composting of selected biodegradable matter. A co-generation of electricity and low-temperature heat from incineration was considered in this study as well as the realisation of a district heating system in the areas surrounding the incinerators. Moreover the REMS takes into account also wastes from Agriculture (plastic

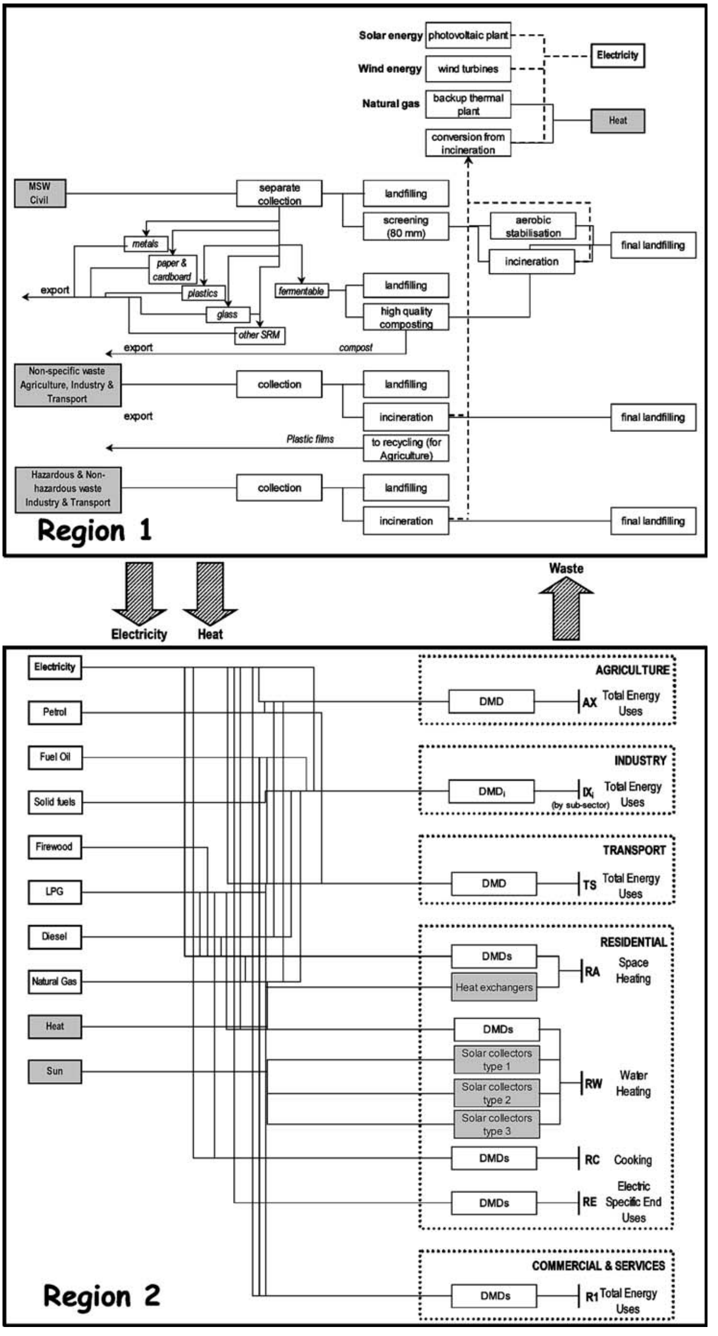


Fig. 1. Aggregated representation of the REMS of MARKAL-Basilicata.

films), and nonhazardous/hazardous solid wastes for Industry and Transport. Also in this case, incineration with energy recovery was considered as the alternative option to landfilling, whereas matter valorisation (by export and recycling in neighbour regions) was also taken into account for agricultural plastics.

With regard to the electric energy production, photovoltaic and wind power were introduced besides power plants and energy import (Fig. 1). Moreover, waste incineration represents a further energy source, contributing to electric energy and low-temperature heat production.

As concerns Residential, thermal uses (space heating, cooking, water heating) and electrical uses (lighting, domestic electrical appliances, general services for households) of dwellings were modelled. According to the national decree on final uses [26] an improvement of the actual technology network was taken into account to explicit the substitution of obsolete devices (e.g. domestic electrical appliances and boilers) and the effect of insulating interventions on existing buildings. Moreover, two main renewable technologies were taken into account for new residential areas: heat exchangers for water and space heating of districts on the surrounding neighborhood of incineration plants, and solar collectors for water heating. In particular, three different options of solar collectors were modelled, depending on their installation (on pitch roofs, on flat roofs or in gardens) and characterised by different costs. On the other hand, the energy uses of commercial activities, offices and several services (hotels, hospitals, universities, sports complex) were considered in an aggregate way to take into account the energy and waste flows of the local Commercial and services sector.

A "black-box" modelling of Agriculture, Industry (twelve sub-sectors) and Transport (two sub-sectors) was adopted to take into account input flows of energy vectors and wastes in output, according to the subdivision of the energy regional balance [27]. Such a representation will allow a further desegregation of these sectors as soon as the related sector plans will be available and to fulfil new research issues.

### 3.1. Choice of scenarios

The multi-period structure of MARKAL allows users a detailed analysis of possible developments of the local energy system on a chosen time horizon, describing in each time period, the available technologies and resources (fossil fuels, waste, etc.).

With regard to MARKAL-Basilicata, a 27-year time horizon (1996–2022, set up by nine 3-year slice periods) was considered for assessing the consequences of carbon dioxide reduction on the local anthropogenic system. The length of the time horizon was chosen in order to take into account the average life of devices and, thus, the effects of technological turnover on the local system. A constant end-uses demand was assumed and future costs were discounted to present values using a 4% money discount rate.

A scenario by scenario analysis was performed to analyse the consequences of exogenous environmental constraints upon the model and, in particular, to investi-

Table 1
Main characteristics of the analysed scenarios

| Scenarios: | BASE | Post-Kyoto | | | |
|---|---|---|---|---|---|
| Main features: | | $CO_2$-3.7 | $CO_2$-4.1 | $CO_2$-4.3 | $CO_2$-4.4 |
| Civil | Technological turnover for domestic electrical appliances and boilers<br>Insulating interventions on existing buildings | | | | |
| Conversion sector | | Wind power and photovoltaic<br>Solar collectors<br>District heating | | | |
| Waste management | Only landfilling | Integrated WMS<br>Electricity and heat recovery from incineration | | | |
| | Increasing target for separate collection of secondary materials from private households (from 5% to 35%) | | | | |
| Imposed restrictions | Nothing (do nothing scenario) | No landfilling for untreated waste (from the III time period) | | | |
| | | 3.7% reduction of total $CO_2$ | 4.1% reduction of total $CO_2$ | 4.3% reduction of total $CO_2$ | 4.4% reduction of total $CO_2$ |

gate on the possible share of renewable energy technologies. Table 1 gives an overall picture of the main differences among the analysed scenarios. The baseline scenario (BASE) is characterised by the absence of environmental constraints, an efficiency improvement due to technology turnover in the households and by a progressive increase of separate collection of waste (aluminium cans, paper and cardboard, plastics, glass, and fermentable matter), from the actual 5% (I period) up to the legislative target 35% (from IV period).

An environmentally constrained scenario (Post-Kyoto) was introduced to analyse the effects of carbon dioxide restrictions on the technological configuration of the energy system, calculating the emission levels of other air pollutants. For the Post-Kyoto scenario, further renewable conversion technologies were modelled as well as the adoption of an integrated waste management system, in compliance with national laws [25]. Therefore, the cases $CO_2$-3.7, $CO_2$-4.1, $CO_2$-4.3, $CO_2$-4.4 investigate, respectively, on a 3.7%, 4.1%, 4.3%, and 4.4% abatement reduction of the total $CO_2$ emissions, imposed (and calculated) on the overall time horizon.

## 4. Results

### 4.1. Use of energy sources and technologies

The primal solutions of MARKAL generated models provide the user with the optimal levels of activities (amounts of energy and materials flows, installed technologies), emissions of pollutants and costs. This information is reported on a one-year base (the central year of each time period) as well as for the entire time horizon (discounting opportunely all the cost components), supporting energy analysts with a detailed description of the suggested strategies for optimal resources use.

At the same time, the dual solution allows energy analysts to get an insight into the economic consequences of the model choice. It provides, in fact, the shadow

prices of resources and the reduced costs of not-marginal technologies, which are very useful in the definition of economic strategies (taxes, tariffs, incentives...) for carrying out the optimal strategies of resources management suggested by the model.

The main results obtained for the Base and the Post-Kyoto scenarios are discussed in the following paragraphs, pointing out the main changes in the mix of energy vectors and technologies, and the related economic and environmental implications.

#### *4.1.1. The Base scenario*

The reference scenario is essential in order to define the optimal basic configuration of the energy system in a ‘‘business as usual’’ configuration, and to find out the no-regret options, that is, the low-cost alternative technologies for a better resources management.

Particular importance was given to the discussion of the results obtained for the Waste management system and the Civil sector, which contribute significantly to the anthropogenic atmospheric emissions and are interested by relevant changes in the legislative framework.

With regard to the Waste management system, in absence of superimposed environmental and legislative constraints, the optimisation routine reproduces the actual configuration of the system, in which landfilling is the marginal option, that is, the most cost-effective one, for all the waste flows. Moreover the increasing target of separate collection, which also involves selected fermentable matter (food scraps from refectories, pruning residuals, etc.) from the II time period entails a production of high quality compost that varies between 7000 and 12 000 tonnes per year, respectively, for a 15% and a 35% target of separate collection.

As concerns the Civil sector, a 13.7% reduction in energy use is observed, due to the technological turnover and insulation, which leads to an overall 4% reduction of the fossil fuels use for the regional system. In particular, the contribution of insulation is about 12.4 kton and the effect of energy saving coming from efficiency improvement is about 8 kton.

Fig. 2 shows the trend of energy uses in the Civil sector on the analysed time horizon. It can be noted that a decrease of fossil fuels use from the second time period (2000) and a relevant reduction of LPG (−28%) and natural gas (−13%) use. Natural gas and electricity are still the most used energy vectors whereas diesel oil and kerosene are cut off from 2000.

As concerns technology choice for thermal energy production (Fig. 3), from the year 2000 combined single-family LPG and natural gas boilers replace most of the existing devices for dwellings heating, providing about 80% (55 kton/year) of the energy demand. This leads to a considerable reduction in the use of central heating plants (from 11.6 kton/year in 1997 to 1.8 kton/year in the last periods) because these technologies (most of them diesel oil fuelled) are also characterised by higher maintenance costs and a lower versatility with different users requirements.

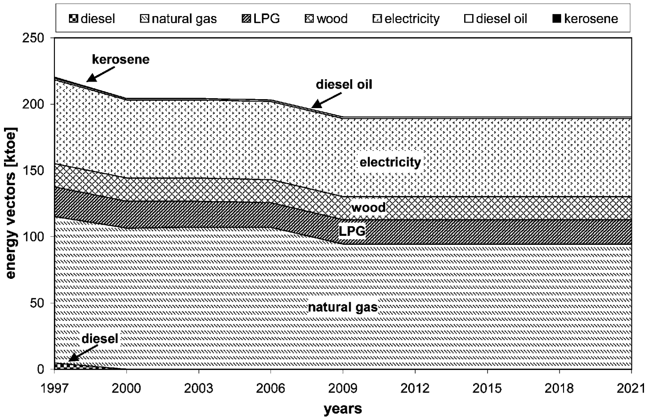


Fig. 2. Use of energy vectors in the reference scenario.

As concerns water heating, the most widespread technologies are electric boilers (61%), which are also used as back-up systems, followed by natural gas boilers (21%).

Also, the Commercial and services sector is characterised by a large use of natural gas devices for thermal energy production, which substitute the existing diesel oil and LPG technologies, thanks also, to the diffusion of the regional natural gas pipeline.

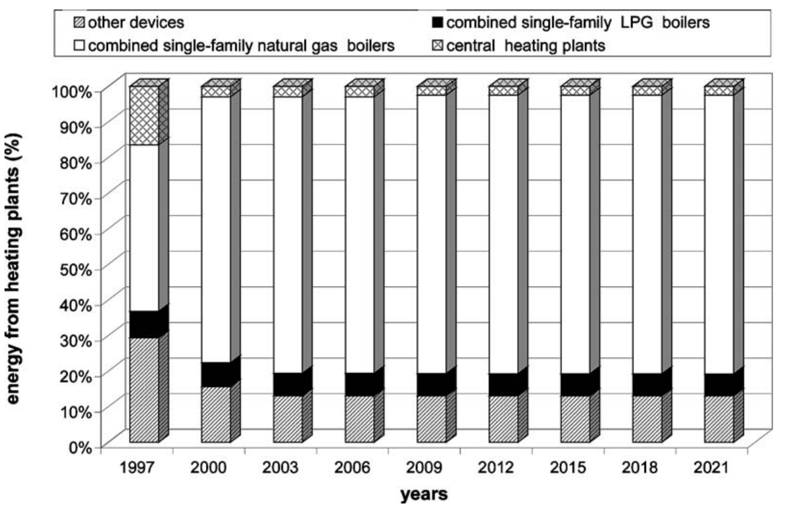


Fig. 3. Optimal mix of heating technologies in the reference scenario.

*4.1.2. The Post-Kyoto scenarios*

The assessment of the potential reduction of carbon dioxide on a local scale is important to evaluate the contribution of local systems to the achievement of the national KP's targets, according to the "bottom-up" approach suggested by Agenda 21. Moreover, the analysis of $CO_2$-constrained scenarios allows one to assess the feasibility of energy saving interventions and renewables use, whose investment costs are often not balanced by savings in operating costs.

For the $CO_2$-4.4 case, a 21% reduction of fossil fuels use is achieved by promoting relevant changes in the waste management system as well as in the technology configuration of both the supply and demand side.

The main actions involve, on the supply side, the installation of a district heating grid and renewable technologies for the production of electricity. Fig. 4 shows the contribute of the different technologies to the overall electricity production (220 kton/year); it can be seen that renewables technologies (photovoltaic, wind energy) contribute to about 14% of the supply.

Also in the demand, sectors are characterised by substantial changes in technology use. Heat exchangers, an increase of technologies efficiency, a large use of insulation interventions, and the use of thermal solar in the Residential sector. These changes have repercussions on the overall regional energy system. Referring again to the maximum $CO_2$ reduction case of the Post-Kyoto scenario, a substantial reduction in the total energy use compared to the BASE scenario can be noted (Fig. 5). In particular, a further 6% of energy saving can be achieved saturating the insulation level of existing buildings and carrying out district heating grids for new residential areas, to satisfy part of the thermal energy demand.

Fig. 5 shows the fossil fuels mix in which an interesting change from period III can be noted. This is due to the start up of incinerators with energy recovery. In particular the use of heat induces a 11% reduction in the use of natural gas (which therefore satisfies the 39% of the demand).

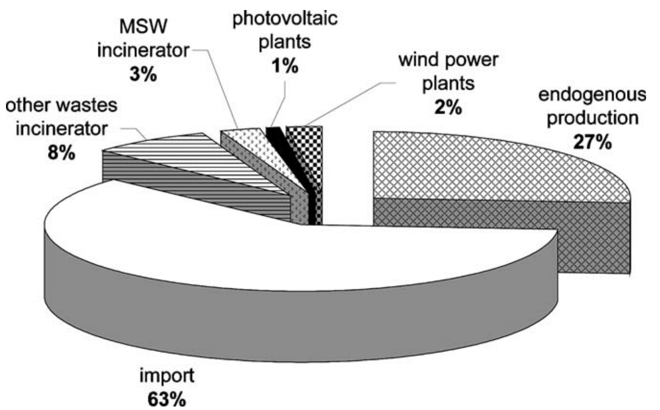


Fig. 4. Electric energy production in the CO2-4.4 case of the Post-Kyoto scenario.

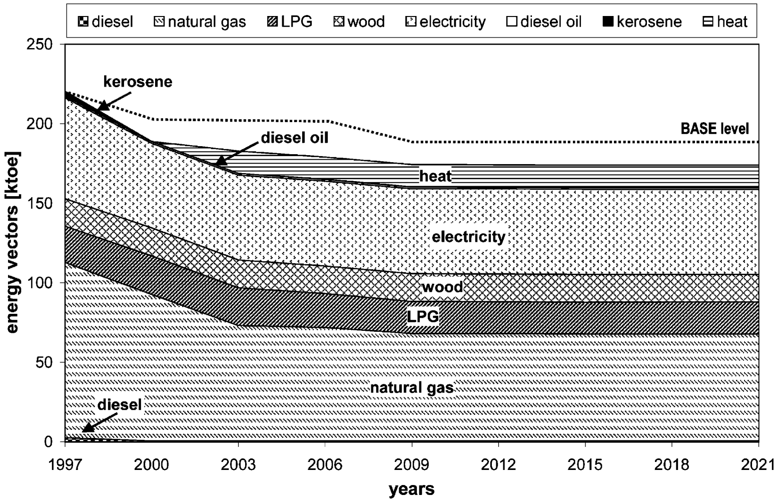


Fig. 5. Use of energy vectors in the CO2-4.4 case of the Post-Kyoto scenario (the dotted line refers to the total energy level of the Base scenario).

As regards the Civil sector, these trends are explained analysing the optimal mix of technologies chosen by the model for satisfying the thermal energy demand for space heating (Fig. 6). The average contribution (calculated on the last seven time periods) of technology options is the following: 47% combined single-family natural gas boilers, 19% heat exchangers, 18% other devices (stoves, fireplaces), 5% combined single-family LPG boilers (−29% compared to the actual situation), and

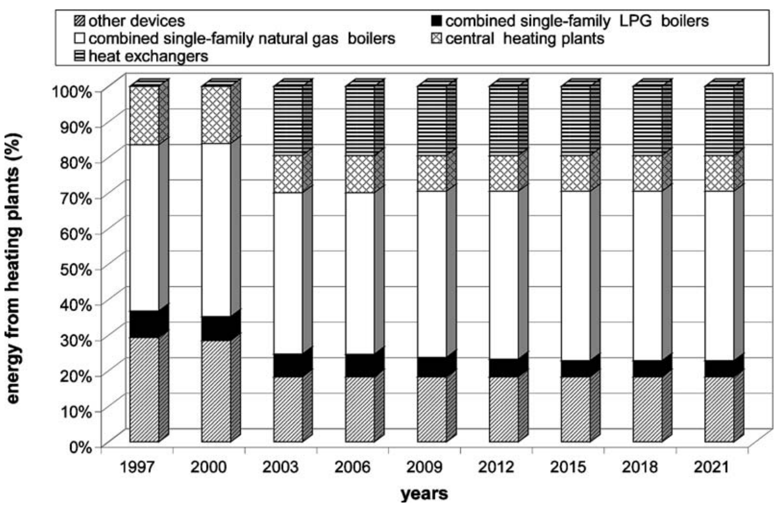


Fig. 6. Optimal mix of heating technologies in the Post-Kyoto scenario (CO2-4.4 case).

10% centralised heating plants. The $CO_2$ restrictions point out the importance of promoting interventions concerning the improvement of buildings' insulation, which allows the system a reduction in the fossil uses to 16.6 kton, in the $CO_2$-4.4 case.

As concerns water heating, some changes in the technologies choice can be noted with respect to the BASE scenario: the electric water heating systems, which previously represented the main choice, are completely substituted by other technology options, according to the following mix: 68% solar collectors, 16% combined single-family natural gas boilers, 14% combined single-family LPG boilers, and 2% heat exchangers.

### 4.2. *Costs analysis*

Costs analysis represents an important step in the results analysis because it allows modellers to better understand the model choices, outlining the key parameters in changing the mix of fossil fuels and technologies, and to provide decision makers with an economical assessment of key measures and strategies [28].

The trade-off curves of Fig. 7 represent the increase of the total discounted system cost in relation to more severe carbon dioxide restrictions. Beside the $CO_2$ curve, a second curve points out the trend of the carbon dioxide equivalent ($CO_{2eq}$), obtained by also taking into account the global warming potential (GWP) of methane emissions according to the IPCC guidelines [29].

The $CO_{2eq}$ trade-off curve shows a 6.33% total reduction corresponding to the $CO_2$-4.4 case. The cost ranges from 15 659 MEuro of BASE scenario to 18 291 MEuro (+16.8%) of $CO_2$-4.4 case, to which the maximum percentage of reduction achievable for the investigated case correspond. The average cost per unit of $CO_2$ emission reduced varies from 198 Euro/toe in the $CO_2$-3.7 case to 701 Euro/toe $CO_2$-4.4 case.

The energy system cost increase is mainly due to investments in new technologies and energy saving options, and it can be emphasised by dual cost solutions analy-

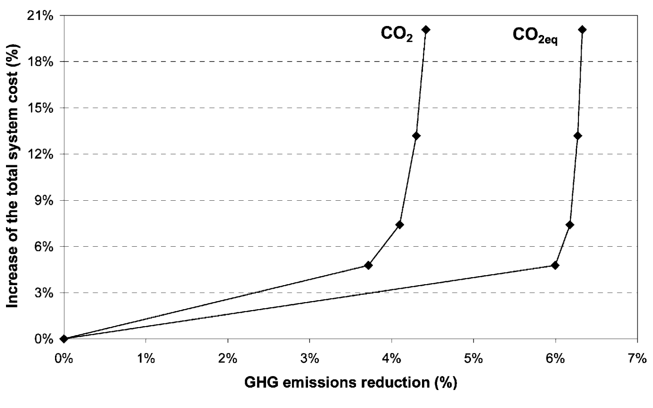


Fig. 7. Trade-off curves: Total system cost vs. $CO_2$/$CO_2$eq emission.

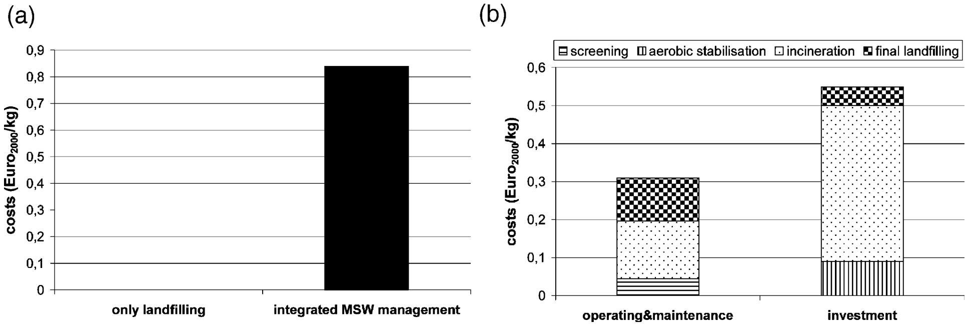


Fig. 8. Reduced costs of waste processing technologies for MSW: comparison between landfilling and integrated system (a) and contributions of different technologies to the integrated configuration (b).

ses. In particular, reduced costs of technologies permit an assessment of the economic feasibility of those options which produce the same commodity, resuming the real market price differences as well as their availability and market boundaries. On the other hand, the shadow prices determine the market value of resources, taking into account the system boundaries and the exogenous constraints. In particular, shadow prices analysis is important to assess the applicability of environmental fees/taxes on the use of fossil fuels (e.g. the carbon tax) but it is also important to promote technological innovation for environmental recovery.

As concerns the results obtained in this study, in the Base scenario waste management is characterised by reduced costs that are zero for landfilling and positive for an integrated waste processing system. In particular Fig. 8(a) shows the reduced costs for municipal solid waste (MSW) management, which are mainly determined by both investment and operating and maintenance costs of incinerators, considerably higher than those of aerobic stabilisation (Fig. 8(b)).

With regard to dwelling heating, combined single-family natural gas boilers are the marginal technology in the BASE scenario (Fig. 9(a)). Nevertheless, the

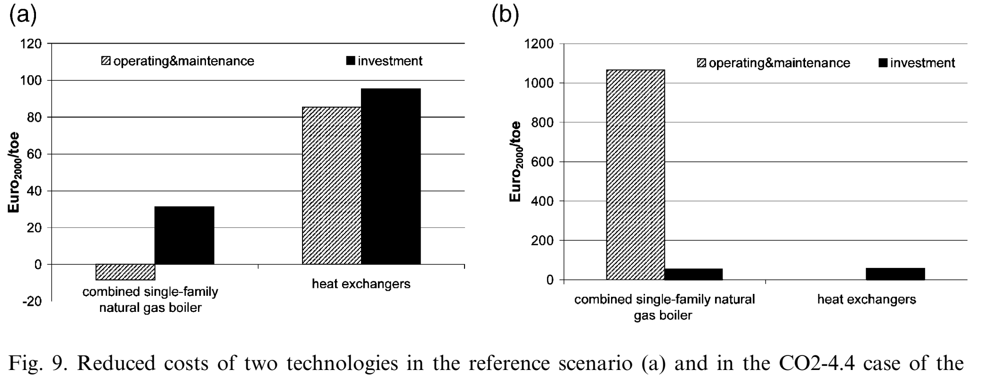


Fig. 9. Reduced costs of two technologies in the reference scenario (a) and in the CO2-4.4 case of the Post-Kyoto scenario (b).

Table 2
Average shadow prices of fuels and $CO_2$

| Energy vector/ emissions | Unit | Market price 2000 | $CO_2$-3.7 | $CO_2$-4.1 | $CO_2$-4.3 | $CO_2$-4.4 |
|---|---|---|---|---|---|---|
| Diesel | Euro/toe | 801 | 1361 | 19258 | 30337 | 36095 |
| LPG | Euro/toe | 1033 | 1510 | 17179 | 26885 | 31928 |
| Kerosene | Euro/toe | 940 | 1487 | 19217 | 30198 | 35905 |
| Natural gas | Euro/toe | 455 | 884 | 14906 | 23592 | 28106 |
| Fuel oil. | Euro/toe | 398 | 918 | 19646 | 31246 | 37273 |
| Heat | Euro/toe | 841 | 209 | 16409 | 26429 | 31586 |
| Electricity | Euro/toe | 1503 | 1887 | 54230 | 86648 | 103494 |
| Carbone dioxide | Euro/ton | | 2952 | 5903 | 9593 | 12544 |

constraints on $CO_2$ emissions moves the marginality level so that in the case of $CO_2$-4.4 the marginal technology is represented by heat exchangers (Fig. 9(b)).

In particular, the gap between the costs is strongly reduced by taking into account the high shadow prices of $CO_2$ and natural gas.

In fact, the environmental constraint causes an increase of all the fossil fuels shadow prices, which is proportional to their potential contribution to $CO_2$ emissions. On the other hand, the shadow prices of $CO_2$ expresses the monetary equivalent of the pollutant emissions avoided (e.g. per ton $CO_2$-emitted) with regard to the analysed system.

As shown in Table 2, shadow prices of all energy vectors increase as soon as the $CO_2$ restrictions become more severe. It can be noted that fuels with higher emission factors (such as fuel oil) are those with the most considerable increase of shadow prices.

### 4.3. Environmental effects

To verify the achievement of the Kyoto Protocol's objectives it is necessary to compare the 2010 emission levels to the 1990 ones. Considering that in Italy the average per capita level of greenhouse gases has increased from 1990 to 1997 [30] the comparison to the first year of the analysed time horizon (1997) is still correct. Table 3 shows that the no-regret options included in the Base scenario allow a

Table 3
Emissions reduction achieved in 2010 compared to the 1997 levels

| Scenarios | Base | Post-Kyoto | | | |
|---|---|---|---|---|---|
| Cases | | $CO_2$-3.7 | $CO_2$-4.1 | $CO_2$-4.3 | $CO_2$-4.4 |
| $CO_2$ | −5.03% | −9.97% | −10.01% | −10.51% | −10.51% |
| $CH_4$ | 0.00% | −82.29% | −82.29% | −82.29% | −82.29% |
| $CO_{2eq}$ | *−4.26%* | *−21.17%* | *−21.20%* | *−21.62%* | *−21.62%* |
| CO | −0.06% | 0.01% | 0.01% | 0.01% | 0.01% |
| NOx | −0.15% | 0.26% | 0.26% | 0.24% | 0.24% |
| SOx | −0.33% | −0.17% | −0.17% | −0.22% | −0.22% |
| TSP | −0.07% | 0.01% | 0.01% | 0.00% | 0.00% |
| VOC | −0.05% | −2.38% | −2.38% | −2.38% | −2.38% |

basic 5% reduction of carbon dioxide, comparing the emission levels at 2010 with those of the base year (1997). As concerns the environmental constrained scenario, a more remarkable reduction of greenhouse gases can be achieved both in terms of $CO_2$ (up to 10.5%) and $CO_2$ equivalent (up to −21.6%) by drastically changing the waste management system (passage from landfilling to an integrated system) and reorganising thermal energy demand devices in the Civil sector (installation of district heating grids and renewable technologies).

As concerns local air pollutants, we considered the energy-related emissions of carbon monoxide (CO), nitrogen oxide (NOx), sulfur oxide (SOx), particulates (TSP) and volatile organic compound (VOC). Comparing again the emission levels at 2010 with those of 1997, it can be noted that the more efficient configuration of the Civil energy end-uses causes an overall reduction of all the considered local air pollutants in the BASE scenario. These environmental benefits are reduced by the negative effects of incineration which leads to a general increase of all the pollutants related to waste burning.

## 5. Conclusion

This research was aimed at supporting energy analysts and energy planners in the definition of sound climate strategies on a local scale. In order to assess the possible contribution of local energy systems to the achievement of the national Kyoto Protocol's targets, the MARKAL-Basilicata model was implemented using the regional variant of the MARKAL models generator. Two dummy "regions" were modelled to represent the supply and the demand side and their main feedback of energy and material flows. The implemented model provides a dynamic representation of the main macroeconomic sectors, with particular attention to electricity production, residential end-uses and waste management (the latter based on the results of the sub-system WAMMM model).

Results show that in the reference unconstrained scenario (BASE) technological turnover and mix fuels changes in the Civil sector lead to a general decrease of GHGs and local air pollutants. When a consistent reduction of carbon dioxide emissions is imposed (Post-Kyoto scenario), the model's solution offers a wide range of measures (technology innovation, insulation interventions on existing dwellings, use of renewable energy technologies) which induces a more considerable reduction of the energy-related emissions. An important role is played by the waste management system where the passage towards an integrated configuration in compliance with the national laws gives a positive effect in terms of GHG emissions reduction (because of the landfills biogas avoided) but causes further emissions of local air pollutants due to waste burning.

In particular, the $CO_2$-4.4 case shows a 6.3% total reduction of $CO_{2eq}$ on the whole time horizon (27 years) for Basilicata region, that is, −10.5% of the 2010 annual emissions compared to the 1997 basis. Trade-off curves point out that the average cost of GHG emissions reduction for the local system spans between 198 Euro/ton$CO_2$ (case $CO_2$-3.7) up to 700 Euro/ton$CO_2$ (case $CO_2$-4.4), resulting in

much higher than the average Italian cost (60 Euro/ton$CO_2$ [31]). This is due to the fact that most of the $CO_2$ constraint is charged on the Civil sector, which introduces expensive technological options in order to satisfy the exogenous restriction. Therefore, future developments will deal with a desegregation of the other macroeconomic sectors (in particular Industry and Transportation) and with the definition of policy scenarios that address both global warming and local pollutants [32].

## Acknowledgements

This work was supported by grants from INFM and was part of a research line co-ordinated by Prof. Maria Macchiato. We would like to thank Dr. Giancarlo Tosato from ENEA for his support of this work and his helpful comments.

## References

[1] IPCC. Climate Change 2001: Mitigation—Contribution of Working Group III to the Third Assessment Report of IPCC, 2001.
[2] Ministry for the Environment and Territory. Ratification and implementation of the Kyoto protocol to the Framework Convention of the United Nations on Climate Change, drawn up in Kyoto on 11 December 1997. Italian Law no. 120 of 1 June 2002.
[3] Ministry for the Environment and Territory. Italian Third national communication under the UN Framework Convention on Climate Change, 2002.
[4] CIPE Decision n. 137 19 November 1998. Linee guida per le politiche e misure nazionali di riduzione delle emissioni dei gas serra (National guidelines on greenhouse gases reduction, in Italian).
[5] Conference of the Presidents of Regional Governments and of Autonomous Provinces. Agreement protocol of the Conference of the Presidents of Regional Governments and of autonomous provinces for the co-ordination of policies aimed at reducing emissions of greenhouse gases into the atmosphere. Turin, 5 June 2001.
[6] Reinhard J, editor. A guidebook for advanced local energy planning. Bietigheim-Bissingen, Germany: Fachinstitut Gebäude Klima e.V. (FGK); 2000.
[7] ALEP website: http://www.iea-alep.pz.cnr.it.
[8] Fishbone LG, Abilock H. MARKAL—a linear programming model for energy systems analysis: technical description of the BNL version. International Journal Energy Research 1981;5(4):353–75.
[9] Goldstein GA, Hill D. Getting started with PC-MARKAL and the MARKAL user's support system. New York: Upton; 1995.
[10] ABARE—Australian Bureau of Agricultural and Resource Economics. Answer MARKAL, an Energy Policy Optimisation Tool. User Manual, 1999.
[11] ETSAP websites: http://www.ecn.nl/unit_bs/etsap; www.etsap.org
[12] Seebregts Ad J, Goldstein GA, Smekens K. Energy/environmental modelling using the MARKAL family of models. In: Proceedings of the OR2001 Conference, Energy and Environment Session, September 3–5 2001, Duisburg, Germany.
[13] Bahn O, Barreto L, Büeler B, Kypreos S. A multi-regional MARKAL-MACRO model to study an international market of $CO_2$ emission permits: a detailed analysis of a burden sharing strategy among the Netherlands, Sweden and Switzerland, report no. 97-09. Villigen, Switzerland: PSI, 1997.
[14] Barreto L, Kypreos S. Technological learning in energy models: experience and scenario analysis with MARKAL and ERIS model prototype, report no. 99-08. Villigen, Switzerland: PSI, 1999.
[15] Gielen DJ, Gerlagh T, Bos AJM. MATTER 1.0—A MARKAL energy and material system—model characterisation, report ECN-C-98-085, Petter, The Netherlands: ECN, 1998.

[16] Hamilton LD, Goldstein G, Lee JC, Manne A, Marcuse W, Morris SC, Wene C-O. MARKAL-MACRO: An Overview, report no. 48377. Brookhaven National Laboratories, 1992.
[17] Loulou R., Lavigne D. MARKAL model with elastic demands: application to greenhouse gas emission control. In: Carraro C., Haurie A., editors. Operations research and environmental management. The Netherlands: Kluwers Academic Publishers, 1996:201–220.
[18] van Regermorter D, Goldstein G. Development of MARKAL—Towards a partial equilibrium model. ETSAP Technical paper, 1998.
[19] Ybema JR, Bos AJM, Seebregts AJ. Incorporating the long term risk for deep emission reduction in near term $CO_2$ mitigation strategies. Journal of Hazardous Materials 1998;61:217–27.
[20] Kram T, Gielen DJ, Bos AJM, de Feber MAPC, Gerlagh T, Groenendaal BJ, Moll HC, Bouwman ME, Daniels DW, Worrell E, Hekkert MP, Joosten LAJ, Groenewegen P, Goverse T. MATTER: final report Integrated energy and materials systems engineering for GHG emission mitigation. ECN-C–01-017, Petten, the Netherlands, Netherlands Energy Research Foundation, 2001.
[21] Salvia M, Cosmi C, Macchiato M, Mangiamele LW. aste management system optimisation for Southern Italy with MARKAL model. Resources, Conservation and Recycling 2002;34(2):91–106.
[22] Cosmi C, Macchiato M, Mancini I, Mangiamele L, Masi S, Salvia MT. he management of urban waste at regional scale: the state of the art and its strategic evolution—case study Basilicata region (Southern Italy). Fresenius Environmental Bulletin 2001;10:131–8.
[23] Cosmi C, Macchiato M, Marmo G, Pietrapertosa F, Salvia MC. omprehensive modelling for approaching the Kyoto targets on a local scale. Renewable & Sustainable Energy Reviews 2003;7:249–70.
[24] Fishbone LG, Giesen G, Goldstein G, Hymmen HA, Stocks KJ, Vos H, Wilde D, Zolcher R, Balzer C, Abilick H. User's guide for MARKAL (BNL/KFA version 2.0) BNL-51701, Department of Applied Science, Brookhaven National Laboratory, Upton, New York—USA and Kernforschungsanlage Julich (KFA Julich), Julich—Germany, 1983.
[25] Legislative Decree 1997-02-05 n.22 (Ronchi Decree). Attuazione delle direttive 91/156/CEE sui rifiuti, 91/689/CEE sui rifiuti pericolosi e 94/62/CE sugli imballaggi e sui rifiuti di imballaggi (National guidelines for the actuation of the 91/156, 91/689 and 94/62 EU directives, in Italian).
[26] Ministry of Productive Activities. Ministry for the Environment and Territory. Ministerial Decree 2001-04-24 Determination of the quantitative objectives for increasing energy efficiency in final uses, 2001.
[27] Rie srl. Piano Energetico della Regione Basilicata (Basilicata Regional Energy Plan, in Italian), 1998.
[28] Cosmi C, Cuomo V, Macchiato M, Mangiamele L, Salvia M, Tosato G. Cost analysis in the definition of environmental recovery strategies-case study Basilicata Region (Southern Italy). International Journal of Energy, Environment and Economics 2000;9(3):189–209.
[29] IPCC. Technical Summary of the Working Group—I Report, 1995.
[30] ANPA. Emissioni in atmosfera e qualità dell'aria (Atmospheric emissions and air quality, in Italian). Serie Stato dell'Ambiente 6/1999, Roma: Agenzia Nazionale per la Protezione dell'Ambiente, 1999.
[31] ENEA. Il processo di attuazione del protocollo di Kyoto in Italia. Metodi, scenari e valutazione di politiche e misure. [The carrying out of the Kyoto Protocol in Italy. Methods, scenarios and valuation of actions an policies]. 2000.
[32] Proost S, van Regermorter D. Interaction between local air pollution and global warming and its policy implications for Belgium, report no. 2001-16. Villigen, Belgium: Leuven, 2003.